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Case History

Long-term time-lapse microgravity and geotechnical monitoring of relict salt mines, Marston, Cheshire, U. K.

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ABSTRACT

The area around the town of Northwich in Cheshire, U. K., has a long history of catastrophic ground subsidence caused by a combination of natural dissolution and collapsing abandoned mine workings within the underlying Triassic halite bedrock geology. In the village of Marston, the Trent and Mersey Canal crosses several abandoned salt mine workings and previously subsiding areas, the canal being breached by a catastrophic subsidence event in 1953. This canal section is the focus of a long-term monitoring study by conventional geotechnical topographic and microgravity surveys. Results of 20 years of topographic time-lapse surveys indicate specific areas of local subsidence that could not be predicted by available site and mine abandonment plan and shaft data. Subsidence has subsequently necessitated four phases of temporary canal bank remediation. Ten years of microgravity time-lapse data have recorded major deepening negative anomalies in specific sections that correlate with topographic data. Gravity 2D modeling using available site data found upwardly propagating voids, and associated collapse material produced a good match with observed microgravity data. Intrusive investigations have confirmed a void at the major anomaly. The advantages of undertaking such long-term studies for near-surface geophysicists, geotechnical engineers, and researchers working in other application areas are discussed.

INTRODUCTION

Many areas within the U. K. (and indeed globally) have had a long history of ground surface subsidence due to near-surface natural dissolution karsts and mining. Subsidence can range from subtle topographic depressions to catastrophic surface collapse (see Waltham et al., 2005; Donnelly, 2006). For subsidence related to mining activities, these can be unpredictable in extent or indeed timing, with collapses occurring during active mining, immediately postmining, or for some time afterward, depending on the mining style, local geology and site conditions, groundwater rebound, and numerous other factors (see Bell et al., 2000).

To detect and characterize near-surface voids and relict mineshafts, traditional geotechnical ground-based methods typically use a combination of historical and modern records and intrusive site investigation data, but these are often expensive and unsuccessful in difficult ground, especially in urban areas that have a varied industrial history (see Reynolds, 2011). Noninvasive near-surface geophysical methods have successfully detected and characterized near-surface voids, relict mineshafts, and low-density ground for geotechnical investigators to then target and remediate (e.g., McCann et al., 1987; Bishop et al., 1997; Wilkinson et al., 2005; Pringle et al., 2008; Tuckwell et al., 2008; Banham and Pringle, 2011; Orfanos and Apostolopoulos, 2011).

Sites of known or problematic subsidence can also be monitored over time, to determine when suspected problem areas become critical and have to be remediated. This has the advantage of being efficient in terms of manpower resources and cost effectiveness, i.e.,

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only remediating problem areas. Time-lapse geophysical surveys have been undertaken for other applications. For example, electrical resistivity surveys have been used to monitor active landslides (Wilkinson et al., 2010a), toxic leachate migration (Rucker et al., 2011), hydrological infiltration (Cassiani et al., 2009), aquifer exploitation (Chambers et al., 2007), and contaminated land (Wilkinson et al., 2010b). Time-lapse ground penetrating radar (GPR) has also been used for fluid migration studies (Birken and Versteeg, 2000), but GPR techniques typically do not have sufficient penetration to monitor mine-related subsidence. Deep sounding electrical (see Denahan and Smith, 1984) and electromagnetic (see Pueyo-Anchuela et al., 2010) methods may penetrate, but there are issues of resolution and overlying heterogeneous ground (Banham and Pringle, 2011). Surface seismic monitoring during active mining has been used (Urbancic and Trifu, 2000), but these are typically expensive to set up and operate and can suffer from resolving the top of cavities but not usually the base.

Researchers have used time-lapse microgravity surveys to observe temporal site changes in other applications of aquifer storage and recovery (Davis et al., 2008), geothermal reservoirs (Sugihara and Ishido, 2008), volcano eruptions (Battaglia et al., 2008), and CO_2 injection studies (Alnes et al., 2008). Time-lapse microgravity

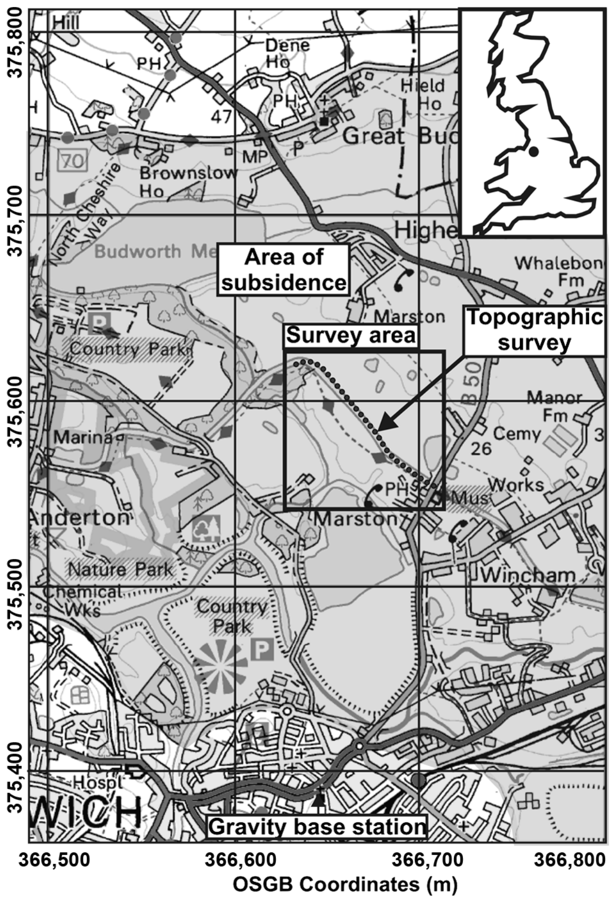

Figure 1. Location map of the Marston field area (box) north of the town of Northwich, Cheshire, with U. K. location map (inset). Also marked are topographic survey sample positions along the Trent and Mersey Canal, subsidence-prone areas, and the gravity base station position. Background image provided by Ordnance Survey/EDINA service. © Crown Copyright Database 2010.

surveys have been undertaken to monitor ground subsidence in which careful data collection and processing were required, but these have been few to-date (see Debeglia and Dupont, 2002; Branston and Styles, 2003). This paper will detail a long-term time-lapse microgravity monitoring study over collapsing salt mines in Cheshire, U. K., where there have been 20 and 10 years of surface leveling and microgravity data collected, respectively. The aim of this paper is to detail the advantages of undertaking such long-term studies for near-surface geophysicists, geotechnical engineers, and for researchers working in other application areas.

BACKGROUND

Industrial mining of rock salt (halite) began in the U. K. in 1672 A.D. Records were not kept until 1873, so it is difficult to determine mining activities before this time (Rochester, 1985). Mining was continuous and was on a large scale around the Cheshire towns of Middlewich, Winsford, and especially Northwich (Figure 1) until the mid-twentieth century (Bell et al., 2000). The only operational rock salt mine in England is the Meadowbank Mine at Winsford in Cheshire (Bell et al., 2000). Triassic (Carnian) Northwich halite is predominantly comprised of pure primary bedded rock salt; however, there are recrystallized rock salt beds with mudstone inclusions (Branston and Styles, 2003). While bringing employment and wealth, poor mining practices led to flooded mines, large-scale catastrophic ground subsidence, and associated surface water-filled hollows, particularly around Northwich (Figures 1 and 2). These practices included not leaving enough roof-supporting pillars behind when physically extracting rock salt (Figure 2a and 2b) and later wild brine pumping, which led to further ground subsidence locally termed "flashes" (Figure 2c and 2d). Branston and Styles (2003) monitor local urban subsidence probably exacerbated by pumping. Modern controlled brine pumping removes salt by solution below dry rockhead, so there is no possibility of circulating groundwater dissolving salt (Bell et al., 2000). By the early twentieth century, most central Northwich town houses were built mounted on jacks so they could be releveled after subsidence events (Rochester, 1985). Attempts to stabilize abandoned salt mines by flooding was unsuccessful and led to continued subsidence as supporting mine pillars dissolved (Adams and Hart, 1992). To remediate Northwich town center, a £28 million ground stabilization program was undertaken from 2004 to 2007, pumping a mixture of pulverized fuel ash (PFA), cement, and salt through boreholes to fill prioritized abandoned salt mines and cavities. Elsewhere, however, problems remain.

This area around the village of Marston, ~2 km north of Northwich, became a major producer of rock salt and associated infrastructure developed from the mid-nineteenth century onward (Figure 3). This development was assisted by the presence of the Trent and Mersey Canal (constructed in 1777) to transport goods. At least seven rock salt mines were in close proximity to this canal section; namely Adelaide, Crystal, Marston Hall, Old Marston (Top) and (Bottom), New Zealand, and Pool Mines (see Figure 4 and Table 1 for details). These mines commercially exploited two shallow level rock salt units, the Top and Bottom salt Beds, respectively that were overlain by ~8 to 25 m of glacial drift and separated by a sandstone/mudstone band locally known as the Thirty-Foot Marl (Figure 5). Natural solution of the top bed salt by groundwater has resulted in these marls becoming brecciated and mechanically weak (Adams and Hart, 1992). Most local mines were flooded by the early twentieth century, as a result of not leaving enough roof-supporting pillars and/or incursions from wild brine pumping (Table 1). Further wild and controlled brine pumping activities subsequently expanded, usually concentrating on the halite top bed, which has since exacerbated ground surface subsidence (Adams and Hart, 1992). The area has also experienced local industrial dumping of chemical lime waste products in the flashes, which has led to large areas becoming uninhabitable (Figures 1, 3, and 4).

A major breach occurred in the Trent and Mersey Canal at Marston in 1953 due to ground subsidence, necessitating the construction of a diversionary cut, which was opened in 1958 (Figure 3). Since then, the canal section and surrounding area have continued to experience subsidence, with the prediction of the location, magnitude, timing, and nature of the subsidence being problematic (Howell and Jenkins, 1976; Fielding, 2001). The local Lion Salt Works Museum structures (Figures 4 and 6a), canal bridges (Figure 6b), and banks (Figure 6d) all show evidence of significant local subsidence. Repeat topographic surveying of this canal section has documented continuing ground subsidence, which was an obvious concern for British Waterways who are responsible for the U. K. canal network. Not only was there potential for a canal breach, but there were also no canal locks for ~40 km, which presented a significant flood risk. Five exploratory boreholes drilled within the Lion Salt Works (Figures 4 and 6a) identified a number of unconsolidated zones and voids within 50 m of the ground surface (Adams and Hart, 1992).

DATA ACQUISITION

British Waterways regularly acquire topographic monitoring data along canal banks around Northwich at ~40 m spacing using survey nails as permanent sample position markers. The Leica™ DN03 precise digital level and 3 m precision staff survey equipment (0.3 mm per km positioning error) are used. Successive topographic surveys were tied to a reference position at Bridge 196 on the canal well outside the survey area. Where monitoring data showed rapid ground subsidence of canal banks, these areas would normally be temporarily remediated by adding ~0.3 m vertical thickness of concrete and associated fill material on the canal banks. This was undertaken in 1998, 2004, 2006, and 2008. This also usually necessitated new survey nails to be added.

The microgravity data were usually collected during the summer months in 2002, 2003, 2004, 2006, 2009, 2010, and 2011 (see Table 2). The same Scintrex™ CG-5 automated microgravity meter was used for all surveys. This instrument automatically corrects for diurnal variation, local latitude and longitude gravity variations, instrument tilt, drift, and local temperature. Microgravity base station readings were also taken at the start and end of each day to linearly confirm that the instrument-calculated temporal drift corrections were correct. The microgravity base station was outside the survey area at an Ordnance Survey reference position at Saint Helen Witton Church in Northwich (position marked in Figure 1). At least three base station readings were acquired in rapid succession each time to ensure base station data reliability, while readings at ~10% of microgravity stations were reacquired to assess survey data quality and repeatability (Table 2).

The initial 2002 canal bank microgravity survey was undertaken using a single 120 s microgravity reading for each station. Subsequent microgravity surveys usually had three measurements of 75 s each per station for data reliability, but this varied depending upon the operator (Table 2). Station spacing was initially 40 m. The spacing was reduced to 5 m over the main area of concern (Figures 4 and 7) to improve target resolution. The larger sample spacing was varied over the monitoring period (Table 2). Care was taken during data acquisition to ensure the Scintrex™ CG-5 gravimeter was sited on hard ground, vertically orientated, and sheltered from wind. Acquisition was delayed if pedestrians or canal boats were passing and was not undertaken if weather forecasts were poor. This resulted in very good station and overall survey and base station sample deviations (sd), ranging from 0.007 to 0.024 mGal and averaging 0.013 mGal. All microgravity station coordinates and a reference position were also accurately surveyed using a Leica™ 1200 Total Station Positioning theodolite to determine absolute positions for the surveys and the data elevation corrections in microgravity data postprocessing. Due to the canal bend, this necessitated two theodolite positions to be sited for each survey. Topographic data of microgravity stations had, on average, 5 mm accuracy (Table 2).

A 2D electrical resistivity imaging profile was collected in 2009, over the largest microgravity low identified, to determine if electrical survey methods could better resolve any near-surface voids as other authors show (e.g., Wilkinson et al., 2005; Banham and Pringle, 2011). A 2D profile could not be taken parallel to the canal due to dense vegetation; therefore, the profile was located on the canal bank itself (Figure 4). However, the resulting inverted resistivity model had a 140% model misfit compared with the collected data, most probably due to the canal bank and site heterogeneity. The resistivity model was therefore deemed unusable.

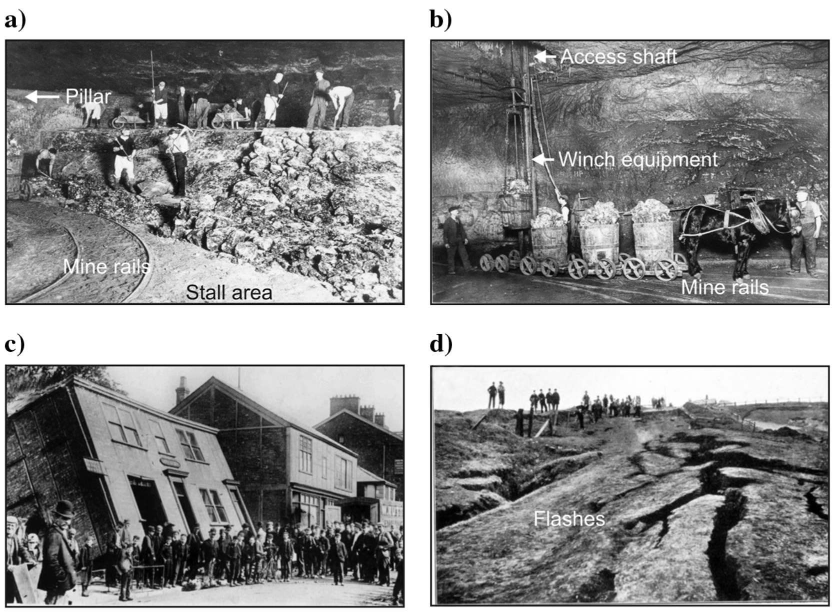

Figure 2. Late nineteenth-century photographs around Northwich showing (a) pillar-and-stall salt extraction, (b) vertical access shaft (unnamed) to salt mine, (c) surface subsidence in the town center, and (d) mine-linked catastrophic surface collapses, termed flashes. Note the building in (c) has been "jacked up" and remains today.

DATA PROCESSING

The topographic canal bank section data had to be corrected for several factors: (1) to work out the correct absolute x, y positions to make all survey sample positions consistent, (2) to work out the difference between the 1991 topographic survey and all subsequent surveys to quantify the relative change, and (3) temporary remedial canal bank work material heights needed to be removed so that the total relative local profile subsidence over the study period could be calculated.

All microgravity survey data were individually processed using in-house software to produce reduced Bouguer anomaly values at each microgravity station for each microgravity survey. Postprocessing checked the microgravity instrument corrections for latitude and longitude, diurnal variations and instrument drift using base station polynomial drift values, and relative elevation using the merged respective gravity station topographic survey data. The same density value of 1.8 g/cm^3 was used to calculate the Bouguer correction for all survey data sets. For stations at which three readings were taken, the readings were compared and averaged, or anomalous readings were removed during despiking following standard methodologies (Milsom, 2007; Reynolds, 2011). Topographic corrections were applied using the data collected during each survey. Each microgravity survey data set was detrended by removing a best-fit linear trend to remove longer wavelength microgravity variations outside the survey area, as suggested by best practice (see, e.g., Reynolds, 2011). Finally, small gravity constant values were added or removed where appropriate for each survey to ensure best fit to the overall average; this was justified on the basis of varying canal water heights between surveys. Available canal water height data from the nearby Anderton Weir indicate a 5.3 ± 0.1 cm height difference on average between 2009 and 2011. Branston (2003) calculates the local topographic effect of the terrain surrounding the canal using the Parker method and finds that it is relatively insignificant (~0.001–0.002 mGal). Furthermore, surrounding terrain effects are eliminated when comparing time-lapse gravity data over the same canal section.

DATA INTERPRETATION

The available site, mine abandonment plan, and associated shaft information (Table 1 and Figures 3, 4, and 5) were used to generate 2D geotechnical lithological models using Cooper™ Grav2Dc v.2.10 modeling software. Rock densities were assigned to respective lithologies using borehole log and published data (Branston, 2003; Milsom, 2007). The rock densities used were (sequentially listed from model surface to base) as follows: 1.275 g/cc for fill, 1.5 g/cc for boulder clay drift, 1.9 g/cc for halite top and bottom beds with 1.2 g/cc for marl interbeds, and 1.0 g/cc for brine-flooded mines.

The latest processed microgravity survey (2011) shown in Figure 8 was also imported so quantitative comparisons could be made between the observed gravity and the calculated gravity from the 2D model. Two models were generated. The initial model presumes the deep flooded mines are still intact, but the Marston old mine shaft entrance has collapsed as documented in 1933 (Figure 9a). The second model was generated using the same microgravity data, altering the initial model to contain two near-surface voids and associated collapse material areas centered ~290 and ~550 m to match observed data (Figure 9b). Modeled brine-filled voids were at ~25 m and ~60 m bgl, respectively, and had the same density as the modeled intact mines (1.0 g/cc). Underlying modeled collapsed material extended down to mine workings (~90 m bgl) and had relatively low densities (1.67 g/cc) as material usually expands after collapse. The second model had an improved data/model rms misfit compared to the initial model (0.011 versus 0.050, respectively).

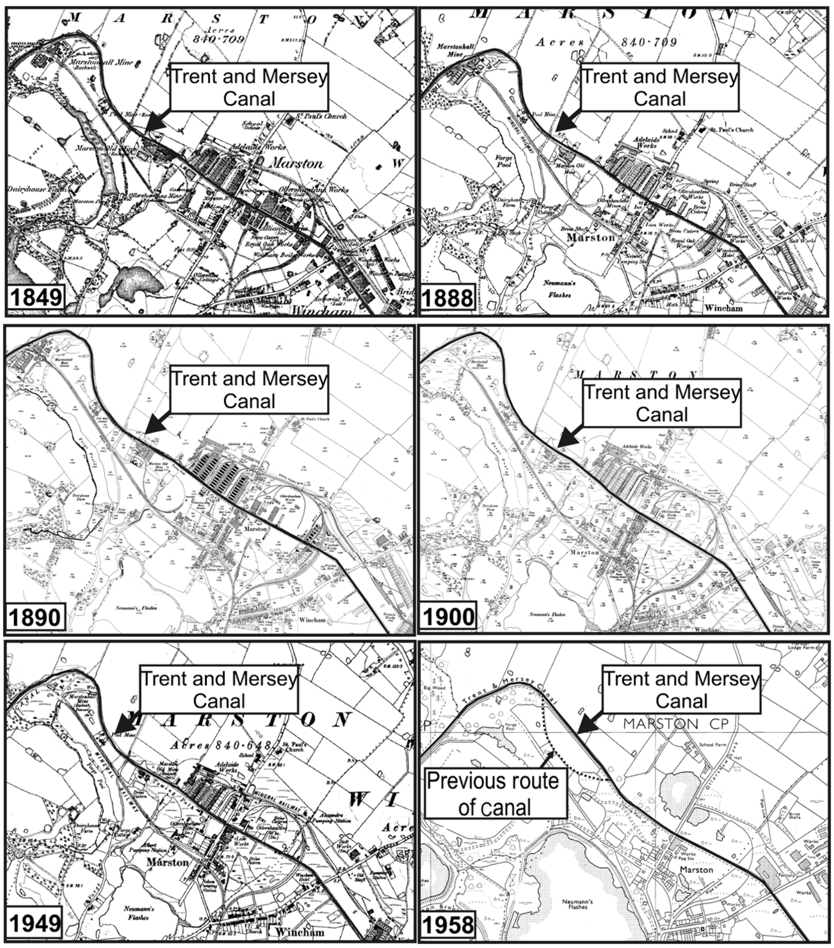

Figure 3. Historical maps of the Trent and Mersey Canal survey area (dated) with survey area marked. Note the rerouting of the canal due to the 1953 breach (1958 map). Images provided by Ordnance Survey/EDINA service. © Crown Copyright Database 2010.

RESULTS

The 20-year processed topographic monitoring data sets of the Trent and Mersey Canal bank section are graphically shown in Figure 7. Topographic survey results indicate consistent ground surface subsidence along certain sections of the canal throughout the survey period. Ground subsidence was relatively rapid between surveys. Between the 2007 and 2009 surveys, the two areas centered at ~175 and ~725 m, respectively, had sudden and significant subsidence. The major subsidence area centered at ~425 m showed consistent and continual rapid subsidence throughout the survey period. The canal bank areas of rapid subsidence necessitated four different areas of temporary remediation to reduce the risk of canal breaches (marked in Figure 7). Canal sections that experienced the most subsidence were somewhat unexpected when compared with the plan abandoned mine locations (compare Figures 4 and 7). Usually in geotechnical investigations, the maximum amount of subsidence is over the central area of mine workings with the rate of subsidence progressively decreasing toward the mine margins (see, e.g., Bell et al., 2000), but the two canal sections experiencing the most subsidence in this study were at the mine margins. The west and east margins of the abandoned Marston old mine (~75 and ~375 m, respectively) experienced ~0.3 to ~0.6 m of surface subsidence with only the west edge of the Adelaide mine (~450 m) experiencing ~0.6 m of surface subsidence. The central areas experienced subsidence ranging between ~0.05 to ~0.25 m (Figure 7). It is suggested that the observed mine subsidence

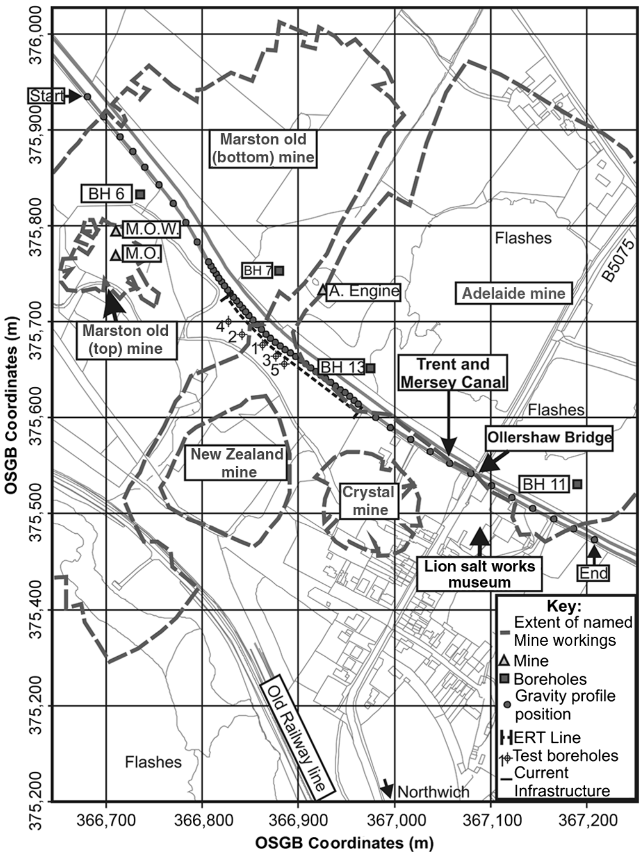

Figure 4. Marston site map (planview) showing current infrastructure, geophysical sample positions, abandoned salt mines (named) and access shafts (initials), and borehole positions (see key). Background image provided by Ordnance Survey/EDINA service. © Crown Copyright Database 2010.

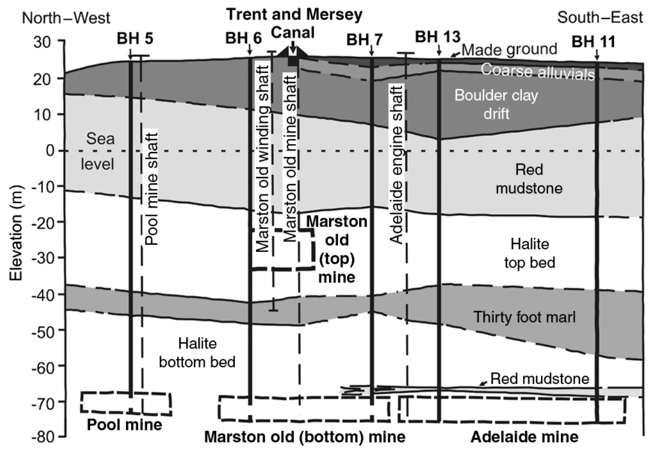

Figure 5. Schematic cross section of survey area created using boreholes and access shaft information (see Figure 4 for locations). Abandoned mines are also shown in their approximate positions (see Figure 4 for locations).

Table 1. Summary of Halite mines within the Marston study area (see Figures 3 and 5). All mines worked the halite bottom bed unless otherwise stated. From Debes (1956) and Wharmby (1987).

Mine	Year started	Year abandoned	Reason abandoned	Workings extent and average thickness	Comments
Adelaide	1850	1928	Catastrophic shaft flood	12.7 ha (6 m)	Overlying works foundered into flooded crater. Open workings remain. Last mine worked.
Crystal	1850	1920	Flooded	0.8 ha (unknown)	260Tn picric acid remain. Shafts filled, and open workings remain.
Marston Hall	1850	1905	Roof fractured a shaft flood	13.1 ha (5.8 m)	1907 surface collapse (4 m) breached canal. Further collapse in 1927. Open workings remain.
Marston Old (top bed)	1777	1920	Flooded with bottom bed mine	0.5 ha (9.1m)	1933 shaft collapsed. 1953 surface collapse breached canal, caused rerouting. Open workings remain.
Marston Old	1781	1924	Shafts and mine flood	12.9 ha (4.9 m)	1933 shaft collapse. 1958 surface collapse breached canal, caused rerouting. Open workings remain.
New Zealand	1870	1908	Flooded	1.3 ha (unknown)	Shafts filled, but open workings remain.
Pool	1850	1939	Flooded	2 ha (unknown)	Shafts filled, but open workings remain.

is being exacerbated by dissolution of relict mine "pillar-and-stall" workings and secondly by preferential fluid flow at mine margins.

The 10-year processed microgravity monitoring data sets of the Trent and Mersey Canal bank section are graphically shown in Figure 8. Microgravity survey results throughout the 10-year survey period consistently indicate a major gravity low anomaly ~ -0.15 mGal, with respect to background values, centered ~425 m along the canal section. This observed negative gravity anomaly also progressively deepened during the observational period by ~0.05 mGal (Figure 8). The major gravity low also correlates with the major subsidence area (see Figures 7 and 8). Less-significant gravity anomalies elsewhere along the profile are not consistent temporally between microgravity surveys. These were probably due to near-surface variations between surveys — possibly other areas experiencing differential subsidence or due to mine water movements. However, data acquisition errors, although minimized as much as possible, cannot be definitively ruled out. For example, the gravity low anomalies at ~250 and ~575 m in the 2011 survey may be due to near-surface variations or data acquisition errors. Average gravity variations between surveys could also be partially attributed to variations in canal water height. The latter need to be accounted for in postprocessing if these data are available. Microgravity data processing removed some longer wavelength gravity variations that would likely be associated with larger-scale ground subsidence movements around the Northwich area, but significant variations between different microgravity surveys are still apparent (Figure 8) as other authors also find (see, e.g., Branston and Styles, 2003).

The initial 2D geotechnical model illustrates that intact mines do generate a microgravity response that broadly follows the observed 2011 microgravity data (model misfit = 0.05 rms), but the major negative anomalies were not replicated by the intact mine model. However, when mine collapse with upwardly propagating voids

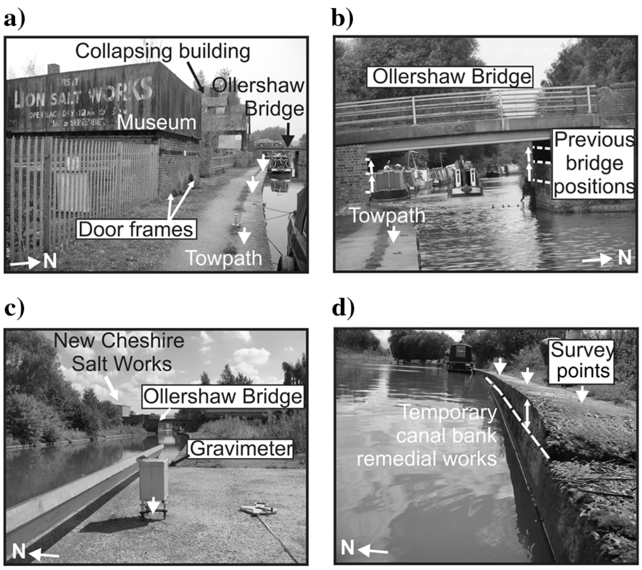

Figure 6. Modern site photographs on south Trent and Mersey Canal bank showing (a) unstable structures within the Lion Salt Works Museum (see Figure 4 for location), (b) subsiding Ollershaw canal bridge 193, (c) view of canal and Scintrex™ CG-5 microgravimeter instrument, and (d) canal bank showing temporary concrete remedial works.

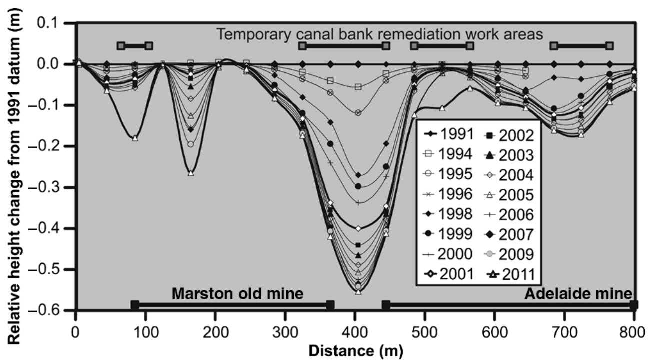

Figure 7. Long-term (20-year) time-lapse geotechnical topographic monitoring data (40 m spaced shown for clarity) of the south bank section of the Trent and Mersey Canal (see Figure 4 for location). Changes are relative to 1991 datum (see key). Note that abandoned mines (Figure 4) and canal bank remedial work (Figure 6c) positions are marked. Note that height data have been corrected for canal bank remediation work (marked).

Table 2. Summary statistics of microgravity data collected during the 2002–2011 study period.

Date of geophysical survey	Survey type	Station total	Station spacing (m)	Station reading duration (s)	Station reobservations (%)	Station average SD error	Base station visits (average no. of repeat readings)	Topographic accuracy average (m)
11/05/2002	Microgravity	56	40 & 5	1×120	21	0.007	4 (2.5)	Not known
08/08/2003	Microgravity	60	40 & 5	1×45	20	0.013	5 (5.4)	Not known
08/09/2004	Microgravity	60	10	1×45	22	0.013	5 (5.4)	Not known
03 & 08/03/2006	Microgravity	50	40 & 5	2×120	10	0.024	5 (5)	0.001
19–20/08/2009	Microgravity	53	40 & 5	3×75	18	0.010	4 (4.5)	0.006
30–31/07/2010	Microgravity	64	20 & 5	3×75	12.5	0.007	4 (4.5)	0.007
19–20/07/2011	Microgravity	63	20 & 5	3×75	14	0.018	4 (4.5)	0.006

and associated low density collapse material are modeled, the calculated gravity response shows a much better fit with the 2011 microgravity data (model misfit = 0.011 rms). The models show generally good comparison with those generated in previous research elsewhere in Northwich (Branston and Styles, 2003, 2006). The remaining model misfit is probably due to data collection variances or smaller near-surface heterogeneities that were not modeled.

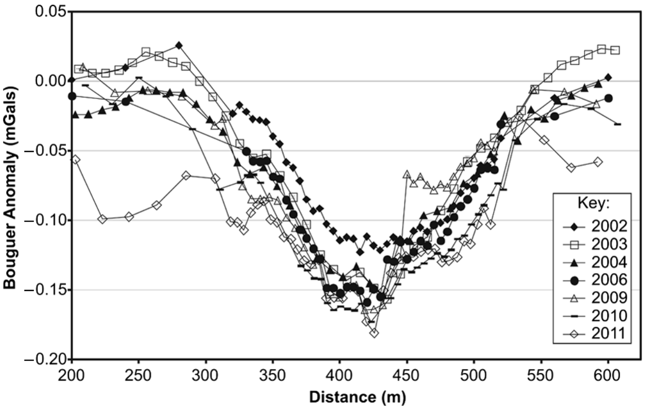

Figure 8. Long-term (10-year) time-lapse microgravity monitoring data of the south bank section of the Trent and Mersey Canal (see Figure 4 for location). Sample point error bars have not been included for clarity (see Table 2). Data have been detrended to remove longer wavelength variabilities.

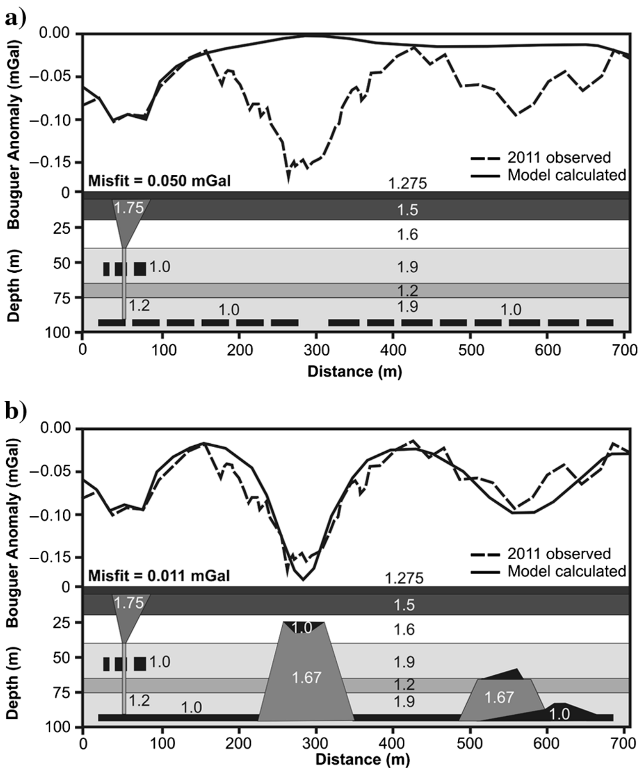

Figure 9. Geotechnical 2D models of survey area (bottom) with 2011 corrected gravity data and model-calculated gravity (top). Models show (a) intact flooded abandoned mines and collapsed Marston Old Mine shaft (left) and (b) collapsing mines to best-fit 2011 corrected gravity data. Note that models have been calibrated to boreholes, mineshaft, and mine abandonment plans (Figure 5) and rock densities (see text). Generated in Cooper™ Grav2Dc v.2.10 software.

The geotechnical and microgravity data show good comparison with the main canal bank subsidence areas over or adjacent to the abandoned salt mine workings. Over the 20-year geotechnical monitoring period, significant surface subsidence occurred over certain canal bank sections. This is an obvious cause of concern for British Waterways, who are responsible not only for the cost of continual remediation, but also for determining the cause of the subsidence and how it could be monitored and remediated if deemed necessary. Continual ground subsidence is also not occurring in the middle of the abandoned mines as would normally be expected (see Bell et al., 2000). The numerical modeling quantified processes in the near surface and showed two specific areas of concern that showed upwardly propagating voids emanating from collapsing mines and natural dissolution. Subsequent exploratory drilling at the 425 m anomaly has confirmed a ~1–5 m vertical void at ~30–40 m bgl depth at test holes 2, 4, and 6 (Figure 4). Clearly this survey area requires continual monitoring to prevent catastrophic collapse and subsequent canal breaches as have occurred previously in this area (Table 1).

This monitoring study will continue on the Trent and Mersey Canal bank section. The topographic surface and microgravity data will provide unprecedented long-term monitoring geotechnical and geophysical data sets and, not least, will assist British Waterways to decide if and when to remediate the local area to prevent catastrophic subsidence collapse.

CONCLUSIONS

The results of a long-term time-lapse microgravity survey (10 years) and topographic survey (20 years) over a section of the Trent and Mersey Canal that overlies collapsing abandoned salt mines in Marston, Cheshire, U. K., were presented. Repeat topographic surveys show subsiding canal bank sections whose elevations could not be forecast from site abandonment plans and surface topographic information alone. Repeat microgravity surveys show a consistent and deepening negative gravity anomaly, which is interpreted to be caused by an upwardly migrating void and associated collapse material. Interestingly, the major subsidence areas are at mine margins rather than in central mine areas as is normally reported. This may be due to a combination of secondary dissolution of relict mine areas, preferential fluid migration pathways, and natural dissolution effects.

Lithological 2D models, integrating information from available mine abandonment and shaft plans were used to generate synthetic gravity profiles, which were quantitatively compared with site-collected microgravity data sets, thus providing a powerful validation tool for the geophysical surveys. Trial intrusive site investigations have confirmed a void at the main anomaly position.

This research illustrates the benefits of using noninvasive, near-surface geophysical and geotechnical techniques for long-term monitoring of problematic subsidence sites. When field data are carefully acquired, processed, and combined with available site data in standard numerical modeling, the results can be used to quantitatively inform interested parties with not only the location and extents of suspected problematic subsidence, but also the potential subsidence rates and timing of potential ground collapses. Not only are the techniques cost-effective monitoring methods, but they are also useful tools for the evaluation and implementation of any subsequent remediation process, assuring that any potential voids are filled and further ground subsidence is minimized.

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